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(54) **SYSTEM AND METHOD FOR MEASURING TORQUE ON A ROTATING COMPONENT**

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,866,462 A *	2/1975	Fraudin	G01L 3/102 73/779
4,566,338 A *	1/1986	Fleming	G01L 3/102 324/209
5,542,304 A *	8/1996	Sasada	B23Q 17/09 73/862.06
5,902,934 A *	5/1999	Sprague	B60G 17/019 73/779
7,845,243 B2 *	12/2010	Poirier	G01L 3/109 73/862.191
8,677,835 B2 *	3/2014	Goto	B62D 5/049 73/862.193
9,146,163 B2 *	9/2015	Sipila	G01L 1/125
10,352,683 B2 *	7/2019	Ouellette	G01N 27/82

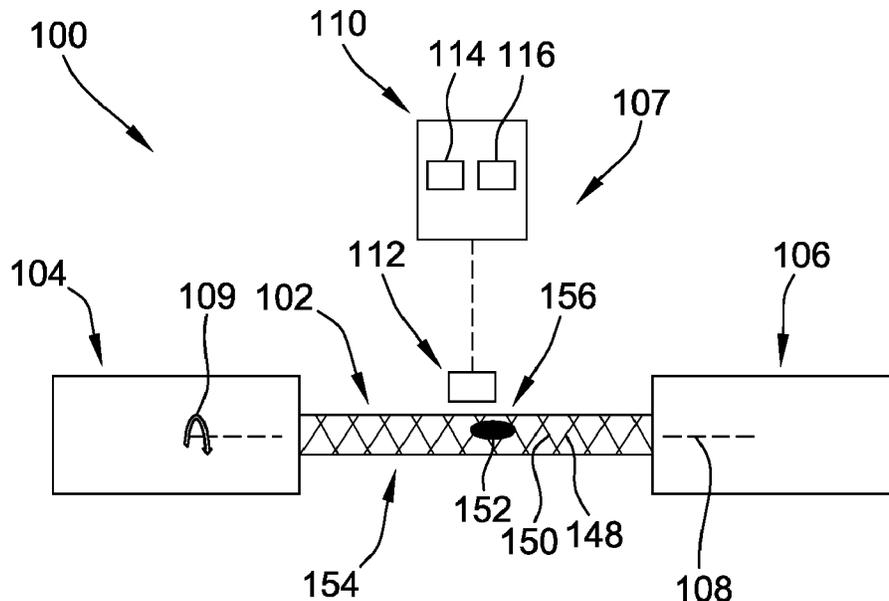
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(57) **ABSTRACT**

A system for measuring torque on a component having a residually magnetized region is provided. The system includes a torque sensor for sensing an electromagnetic characteristic of the component and transmitting a plurality of signals that are indicative of the electromagnetic characteristic. The system also includes a computer communicatively coupled to the torque sensor for receiving the signals. The computer includes a processor and a memory. The processor is programmed to determine, using the signals, that the torque sensor is affected by the residually magnetized region of the component.

17 Claims, 5 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

2007/0089287	A1*	4/2007	Harata	G01L 3/102 29/602.1
2008/0173103	A1*	7/2008	Shimizu	G01L 3/102 73/862.335
2008/0257069	A1*	10/2008	Poirier	G01L 3/109 73/862.191
2009/0025488	A1*	1/2009	Sihler	G01L 3/102 73/862.333
2010/0018328	A1*	1/2010	May	G01L 3/105 73/862.193
2012/0031202	A1*	2/2012	Goto	B62D 5/049 73/862.193
2012/0126833	A1*	5/2012	Dooley	G01N 3/066 324/657
2014/0062488	A1*	3/2014	Stamatescu	G01R 33/0029 324/326
2014/0165741	A1*	6/2014	Sihler	G01L 5/164 73/862.041
2014/0182388	A1*	7/2014	Sipila	G01L 1/125 73/779
2014/0366637	A1*	12/2014	Brummel	G01L 3/105 73/779
2015/0028859	A1*	1/2015	May	G01D 5/145 324/207.15
2015/0323397	A1*	11/2015	May	G01L 1/125 73/779
2016/0245737	A1*	8/2016	Davis	G01N 27/82
2017/0023347	A1*	1/2017	Ouellette	G01B 7/046
2019/0033052	A1*	1/2019	Amineh	G01B 21/08

* cited by examiner

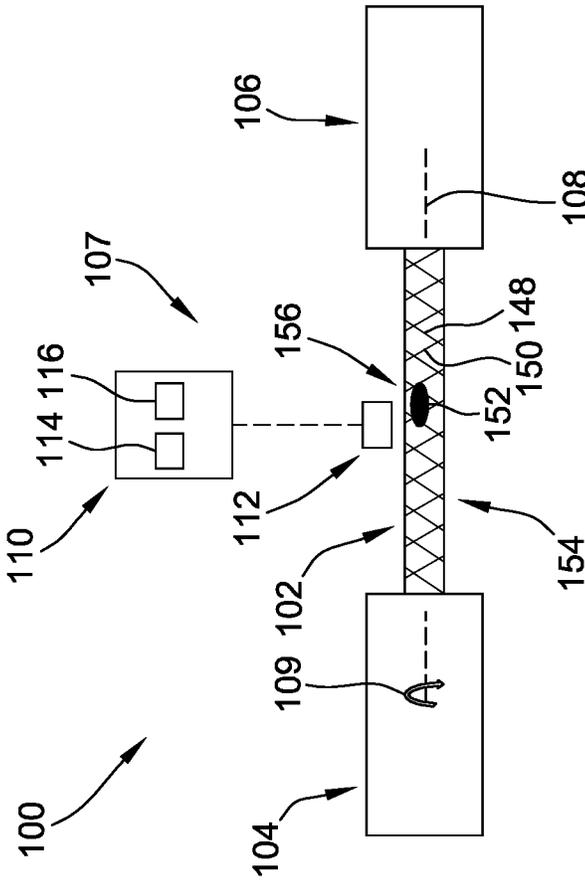


FIG. 1

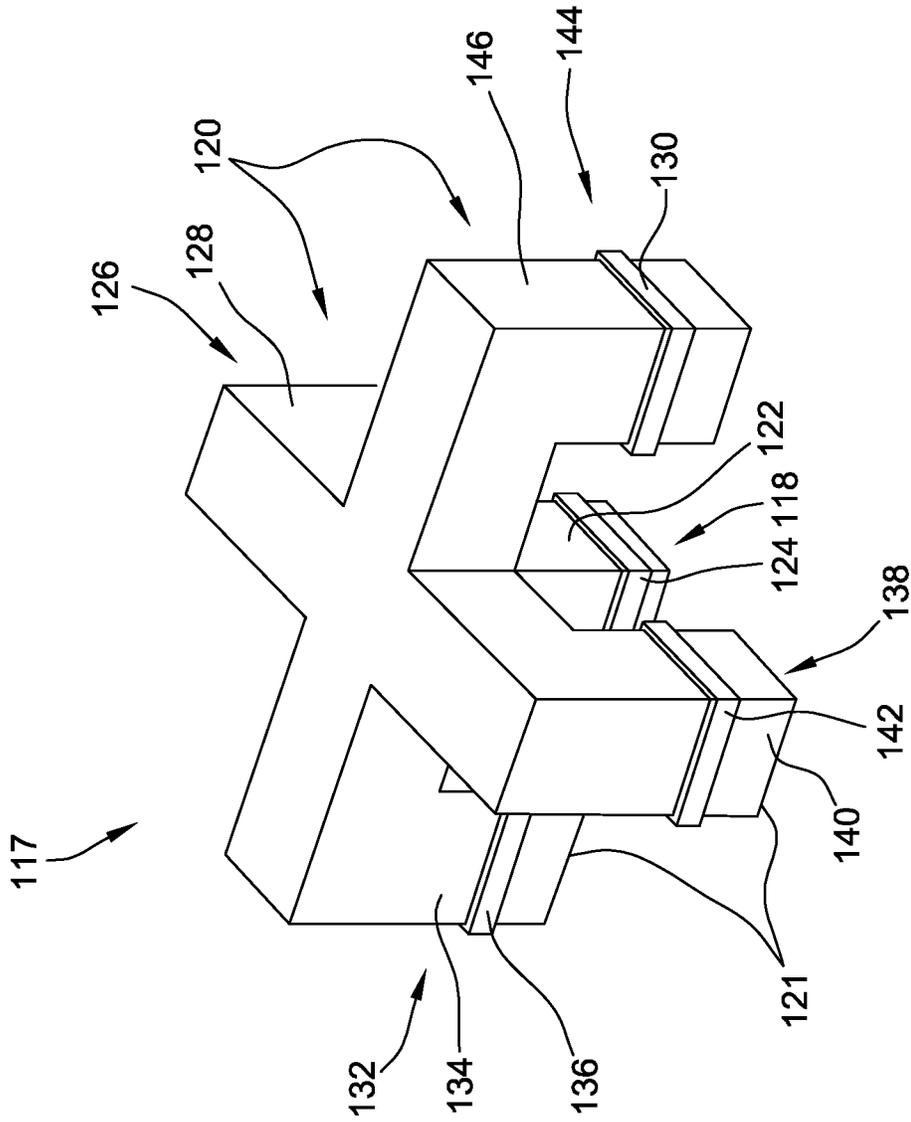


FIG. 2

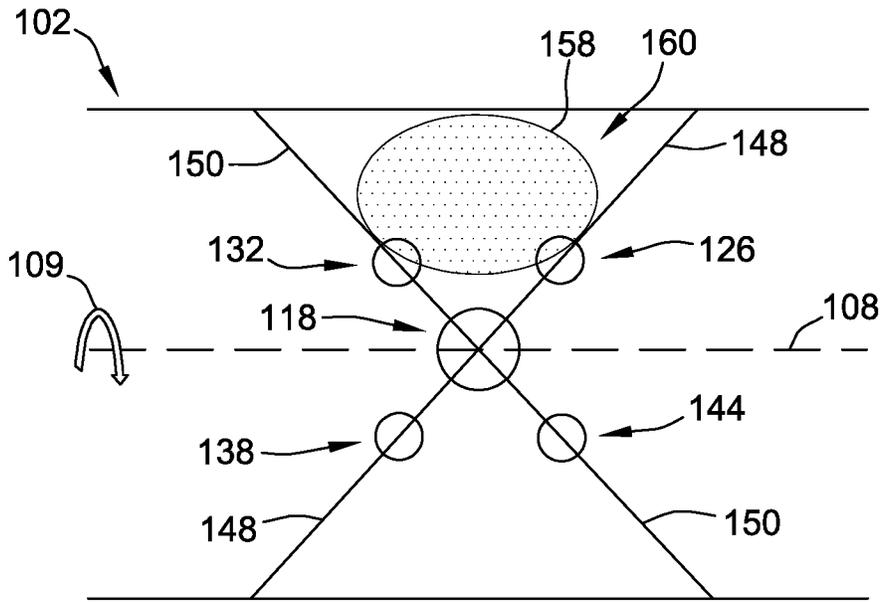


FIG. 3

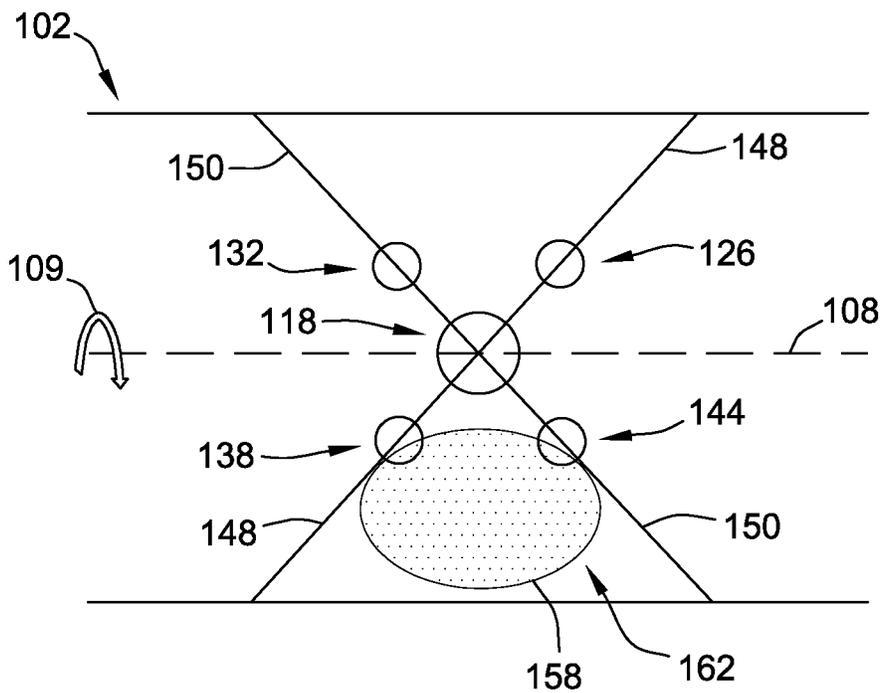


FIG. 4

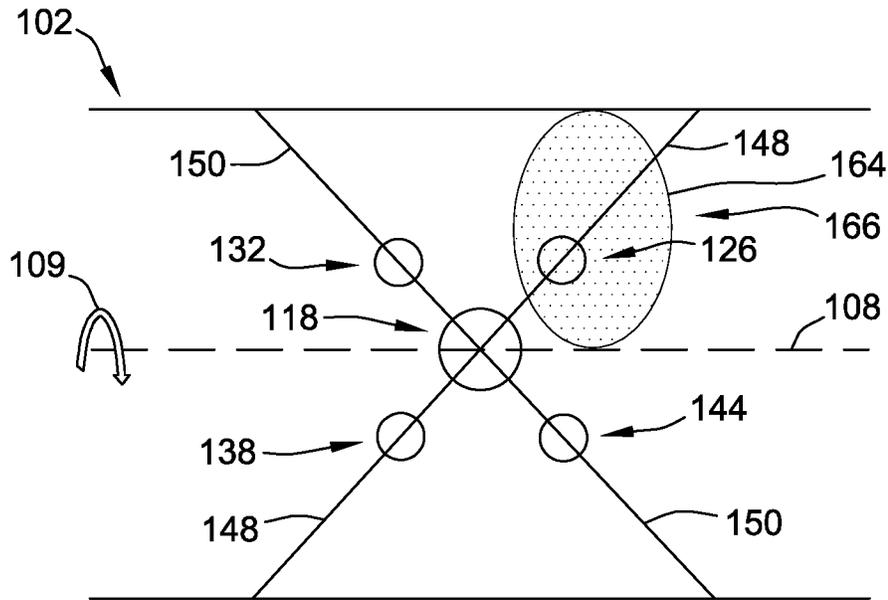


FIG. 5

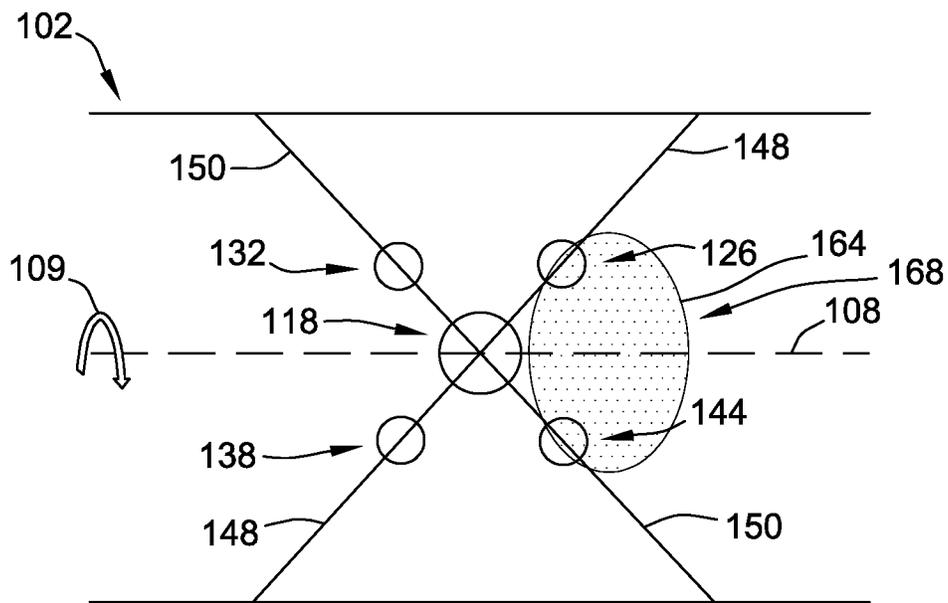


FIG. 6

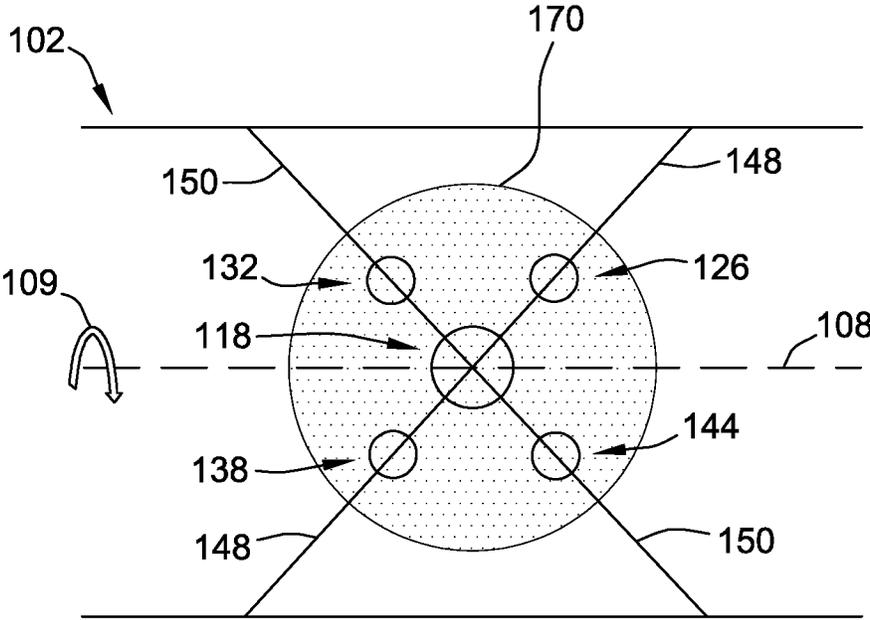


FIG. 7

SYSTEM AND METHOD FOR MEASURING TORQUE ON A ROTATING COMPONENT

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 15/248,180 entitled "SYSTEM AND METHOD FOR MEASURING TORQUE ON A ROTATING COMPONENT," filed Aug. 28, 2016, which is hereby incorporated herein by reference in its entirety.

BACKGROUND

The field of this disclosure relates generally to systems and methods for measuring torque on a component and, more particularly, to systems and methods for measuring torque on a component that is residually magnetized.

Many known ferromagnetic components (e.g., rotatable components such as drive shafts) are fabricated using magnetism. For example, at least some known fabrication techniques include the use of magnetism to test for cracks in a component, to lift (or otherwise handle) a component (e.g., to hold a component in a chuck), or to weld a component (e.g., using alternating or direct electrical current). It is thus common for at least one region of a component to remain magnetized after the fabrication process is complete, and this region of residual magnetism can adversely influence the functionality of devices such as sensors that rely on electromagnetism to sense a characteristic of the component.

SUMMARY

In one aspect, a system for measuring torque on a component having a residually magnetized region is provided. The system includes a torque sensor for sensing an electromagnetic characteristic of the component and transmitting a plurality of signals that are indicative of the electromagnetic characteristic. The system also includes a computer communicatively coupled to the torque sensor for receiving the signals. The computer includes a processor and a memory. The processor is programmed to determine, using the signals, that the torque sensor is affected by the residually magnetized region of the component.

In another aspect, a method for measuring torque on a component having a residually magnetized region is provided. The method includes transmitting, from a torque sensor that senses an electromagnetic characteristic of the component, a plurality of signals that are indicative of the electromagnetic characteristic. The method also includes receiving the signals at a computer that is communicatively coupled to the torque sensor and has a processor and a memory. The method further includes determining, at the computer and using the signals, that the torque sensor is affected by the residually magnetized region of the component.

In another aspect, a computer for measuring torque on a component having a residually magnetized region using a torque sensor that senses an electromagnetic characteristic of the component and transmits a plurality of signals that are indicative of the electromagnetic characteristic is provided. The computer includes a memory and a processor selectively coupled to the torque sensor for receiving the signals, said processor programmed to determine, using the signals, that the torque sensor is affected by the residually magnetized region of the component.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration of an exemplary rotary machine;

FIG. 2 is a schematic perspective view of an exemplary sensor for use in measuring the torque on a component of the rotary machine shown in FIG. 1;

FIG. 3 is a schematic illustration of the sensor shown in FIG. 2 when measuring torque on the component shown in FIG. 1 at a first residually magnetized region of the component having a first angular position;

FIG. 4 is a schematic illustration of the sensor shown in FIG. 2 when measuring torque on the component shown in FIG. 1 at a second angular position of the first residually magnetized region shown in FIG. 3;

FIG. 5 is a schematic illustration of the sensor shown in FIG. 2 when measuring torque on the component shown in FIG. 1 at a second residually magnetized region of the component having a first angular position;

FIG. 6 is a schematic illustration of the sensor shown in FIG. 2 when measuring torque on the component shown in FIG. 1 at a second angular position of the second residually magnetized region shown in FIG. 5; and

FIG. 7 is a schematic illustration of the sensor shown in FIG. 2 when measuring torque on the component shown in FIG. 1 at a third residually magnetized region of the component.

DETAILED DESCRIPTION

The following detailed description illustrates systems and methods by way of example and not by way of limitation. The description should enable one of ordinary skill in the art to make and use the systems, and the description describes several embodiments of the systems, including what is presently believed to be the best modes of making and using the systems. Exemplary systems are described herein as being useful for measuring torque on a component, such as a rotatable drive shaft. However, it is contemplated that the systems have general application to a broad range of systems in a variety of fields other than torque measurement.

The present disclosure provides techniques for an improved torque-measurement system and method. For example, some components are fabricated or otherwise handled using devices that apply a magnetic field to the component. As such, a region of the component may remain magnetized even after the fabrication or handling is complete, and this phenomenon is commonly referred to as residual magnetism. The presence of residual magnetism in a component can have an adverse effect on a sensor that is later used to sense an electromagnetic characteristic of the component such as, for example, when measuring torque on the component during operation of a system in which the component is installed. As described more fully below, some embodiments of the disclosed subject matter relate to a system and a method that are designed to account for (or cancel-out) the effect of such residual magnetism. Other embodiments are within the scope of the disclosed subject matter.

FIG. 1 illustrates an exemplary rotary machine **100**. In the exemplary embodiment, rotary machine **100** has a component **102** (e.g., a drive shaft or drive coupling) operatively coupled between a driver apparatus **104** (e.g., an engine) and a driven apparatus **106** (e.g., a generator), such that component **102** rotates about an axis **108** in a direction **109**. Alternatively, component **102** may be any suitable type of component that is rotatable in any suitable manner for any

suitable purpose (e.g., component 102 may not be a drive component). Although component 102 rotates about axis 108 in the exemplary embodiment, component 102 may not have an axis of rotation in some embodiments.

In the exemplary embodiment, rotary machine 100 also includes a system 107 for measuring torque on component 102. System 107 includes a computing device 110 (broadly a “computer”) and a sensor 112 communicatively coupled to computing device 110 (e.g., via a hardwired connection and/or a wireless connection). Computing device 110 includes a controller or processing device 114 (broadly a “processor”) such as a general purpose central processing unit (CPU), a graphics processing unit (GPU), a microcontroller, a reduced instruction set computer (RISC) processor, an application specific integrated circuit (ASIC), a programmable logic controller (PLC), a field programmable gate array (FPGA), a digital signal processing (DSP) device, and/or any other circuit or processing device capable of executing the functions described herein. The methods described herein may be encoded as executable instructions embodied in a computer readable medium 116 of computing device 110, including, without limitation, a storage device and/or a memory device (broadly a “memory”). Such instructions, when executed by controller or processing device 114, cause controller or processing device 114 to perform at least some of the method steps described herein. The above examples are exemplary only, and thus are not intended to limit in any way the definition and/or meaning of the terms computer, processor, and memory.

FIG. 2 is a schematic illustration of an exemplary sensor 117 for use in system 107. In the exemplary embodiment, sensor 117 is a non-contact, four-branch, magnetostrictive torque sensor having a core element 118 and a plurality of branches elements 120 electrically connected to core element 118 such that core element 118 and branch elements 120 are oriented substantially parallel to one another in spaced-apart relation with core element 118 positioned between branch elements 120. In other embodiments, core element 118 and branch elements 120 may be arranged in any suitable manner and may have any suitable orientation relative to one another.

In the exemplary embodiment, core element 118 has a core shaft 122 and a drive (or excitation) coil 124 that circumscribes core shaft 122. Branch elements 120 include: a first branch element 126 having a first shaft 128 and a first sensing coil (not shown) that circumscribes first shaft 128; a second branch element 132 having a second shaft 134 and a second sensing coil 136 that circumscribes second shaft 134; a third branch element 138 having a third shaft 140 and a third sensing coil 142 that circumscribes third shaft 140; and a fourth branch element 144 having a fourth shaft 146 and a fourth sensing coil 130 that circumscribes fourth shaft 146. In other embodiments, sensor 117 may be any suitable type of sensor constructed in any suitable manner that enables system 107 to function as described herein. For example, in some embodiments, sensor 117 may have any suitable number of branch elements 120 (e.g., sensor 117 may have eight branch elements 120 or another multiple of four branch elements 120), and/or sensor 117 may not be a torque sensor (e.g., sensor 117 may not be a magnetostrictive torque sensor).

In the exemplary embodiment, sensor 117 is designed to be positioned adjacent component 102 such that elements 118 and 120 are oriented towards component 102 and are spaced apart from component 102 at their tips 121, thereby sensing an electromagnetic characteristic of component 102 which is indicative of the torque on component 102. As used

herein, the term “electromagnetic characteristic” of component 102 refers to a characteristic of component 102 that is indicative of its ability to transmit electromagnetic energy (e.g., magnetic flux and/or electric flux). For example, in the exemplary embodiment, the “electromagnetic characteristic” is a magnetic permeability of component 102 as evidenced by a voltage across elements 118 and 120. In other embodiments, sensor 117 may be designed to sense any suitable electromagnetic characteristic of component 102.

When torque is imparted to component 102 for rotating component 102 about axis 108, component 102 experiences at least one circumferential line of tension 148 (shown in FIG. 1) and at least one circumferential line of compression 150 (shown in FIG. 1), such that sensor 117 is selectively positioned relative to component 102 with first branch element 126 and third branch element 138 oriented along the same line of tension 148, and with second branch element 132 and fourth branch element 144 oriented along the same line of compression 150. In that regard, sensor 117 can generate magnetic flux through component 102 from core element 118 to branch elements 120, and sensor 117 can transmit to computing device 110 signals indicative of the voltage sensed at each respective branch element 120.

Using the voltage signals received from sensor 117, computing device 110 can measure the torque on component 102 (e.g., in real time) as set forth in more detail below. In other embodiments, sensor 117 may have any suitable positioning relative to component 102, and may sense (and transmit signals indicative of) any suitable electromagnetic characteristic of component 102 (e.g., a characteristic other than magnetic permeability) that facilitates enabling computing device 110 to measure the torque on component 102 in the manner described herein. Alternatively, sensor 117 may transmit any suitable signal(s) to computing device 110 that facilitate enabling computing device 110 to assess any suitable structural or functional aspect of component 102. For example, computing device 110 may not measure the torque on component 102 in some embodiments (e.g., computing device 110 may instead measure axial stress on component 102).

Notably, as a result of its fabrication process, component 102 has at least one residually magnetized region 152 (shown in FIG. 1), which can alter the magnetic permeability of component 102 (and, therefore, the voltage across elements 118 and 120). For example, if sensor 117 is positioned/oriented as set forth above (i.e., with branch elements 126 and 138 oriented along the same line of tension 148, and with branch elements 132 and 144 oriented along the same line of compression 150) at a segment 154 of component 102 that is substantially free of (or does not have a substantial amount of) residual magnetization, the voltage sensed at first branch element 126 would be the same as the voltage sensed at third branch element 138, and the voltage sensed at second branch element 132 would be the same as the voltage sensed at fourth branch element 144. However, if sensor 117 is positioned/oriented as set forth above (i.e., with branch elements 126 and 138 oriented along the same line of tension 148, and with branch elements 132 and 144 oriented along the same line of compression 150) at a segment 156 of component 102 having residually magnetized region 152, the residual magnetization of region 152 can cause the voltage sensed at first branch element 126 to be different than the voltage sensed at third branch element 138 (or vice versa), and/or can cause the voltage sensed at second branch element 132 to be different than the voltage sensed at fourth branch element 144 (or vice versa). These differences in voltage can impair the ability of computing

device **110** to accurately measure the torque on component **102**. In that regard, as set forth in more detail below, computing device **110** is designed to identify and account for such differences in order to facilitate obtaining an accurate torque measurement despite the presence of residually magnetized region **152** near sensor **117**.

More specifically, in the exemplary embodiment, sensor **117** is designed to transmit to computing device **110**: a first voltage signal V_1 that is indicative of voltage sensed at first branch element **126**; a second voltage signal V_2 that is indicative of voltage sensed at second branch element **132**; a third voltage signal V_3 that is indicative of voltage sensed at third branch element **138**; and a fourth voltage signal V_4 that is indicative of voltage sensed at fourth branch element **144**. Notably, when component **102** is not rotating and sensor **117** is positioned/oriented as set forth above (i.e., with branch elements **126** and **138** oriented along the same line of tension **148**, and with branch elements **132** and **144** oriented along the same line of compression **150**) at segment **154** of component **102**, all voltage signals V_1 , V_2 , V_3 , and V_4 are the same (i.e., $V_1=V_o$, $V_2=V_o$, $V_3=V_o$, and $V_4=V_o$). As such, when torque is imparted to component **102**, the applied stress causes the magnetic permeability of component **102** to change, such that the voltage sensed along the corresponding line of tension **148** increases by the same amount that the voltage sensed along the corresponding line of compression **150** decreases. In other words, voltage signals V_1 and V_3 increase by an amount σ , and voltage signals V_2 and V_4 decrease by the amount σ (i.e., $V_1=V_o+\sigma$; $V_2=V_o-\sigma$; $V_3=V_o+\sigma$; $V_4=V_o-\sigma$). As a result, first voltage signal V_1 remains the same as third voltage signal V_3 , and second voltage signal V_2 remains the same as fourth voltage signal V_4 (i.e., $V_1=V_3$ and $V_2=V_4$).

However, when torque is imparted to component **102** with sensor **117** positioned/oriented as set forth above (i.e., with branch elements **126** and **138** oriented along the same line of tension **148**, and with branch elements **132** and **144** oriented along the same line of compression **150**) at segment **156** having residually magnetized region **152**, component **102** (and, hence, residually magnetized region **152**) rotates about axis **108**, such that residually magnetized region **152** periodically (or continuously) affects the sensing accuracy of at least one branch element **126**, **132**, **138**, and **144**. More specifically, the voltage sensed at an affected branch element **126**, **132**, **138**, or **144** increases relative to the voltage sensed at an unaffected branch element **126**, **132**, **138**, or **144** oriented along the same line of tension **148** or line of compression **150**. For example, if only first branch element **126** is affected by region **152**, then first voltage signal V_1 increases by an amount Δ as compared to third voltage signal V_3 (i.e., $V_1=V_o+\sigma+\Delta$ and $V_3=V_o+\sigma$); if only second branch element **132** is affected by region **152**, then second voltage signal V_2 increases by amount Δ as compared to fourth voltage signal V_4 (i.e., $V_2=V_o+\sigma+\Delta$ and $V_4=V_o+\sigma$); if only third branch element **138** is affected by region **152**, then third voltage signal V_3 increases by amount Δ as compared to first voltage signal V_1 (i.e., $V_3=V_o+\sigma+\Delta$ and $V_1=V_o+\sigma$); and if only fourth branch element **144** is affected by region **152**, then fourth voltage signal V_4 increases by amount Δ as compared to second voltage signal V_2 (i.e., $V_4=V_o+\sigma+\Delta$ and $V_2=V_o+\sigma$).

By comparing voltage signals that would otherwise be the same in the absence of residual magnetization (i.e., by comparing voltage signals V_1 and V_3 , and by comparing voltage signals V_2 and V_4), computing device **110** can thus determine which branch element(s) **126**, **132**, **138**, and/or **144** (if any) are affected by region **152**, and to what extent

such branch element(s) **126**, **132**, **138**, and/or **144** are affected. For example, computing device **110** can determine whether first branch element **126** and/or third branch element **138** is affected by region **152** by subtracting third voltage signal V_3 from first voltage signal V_1 to calculate a signal difference V_{1-3} (i.e., $V_{1-3}=V_1-V_3$). If difference V_{1-3} is greater than zero (i.e., if $V_{1-3}>0$), then computing device **110** determines that only first branch element **126** is affected by region **152**, and computing device **110** thus calculates a modified first voltage signal V_1' that accounts for (or cancels out) the effect of region **152** by subtracting difference V_{1-3} from first voltage signal V_1 (i.e., $V_1'=V_1-V_{1-3}$). If, on the other hand, difference V_{1-3} is less than zero (i.e., if $V_{1-3}<0$), then computing device **110** determines that only third branch element **138** is affected by region **152**, and computing device **110** calculates a modified third voltage signal V_3' that accounts for (or cancels out) the effect of region **152** by subtracting the absolute value of difference V_{1-3} from third voltage signal V_3 (i.e., $V_3'=V_3-|V_{1-3}|$). If, however, difference V_{1-3} equals zero (i.e., $V_{1-3}=0$), then computing device **110** determines that third voltage signal V_3 is equal to first voltage signal V_1 (i.e., $V_3=V_1$). Computing device **110** thus determines either that neither first branch element **126** nor third branch element **138** is affected by region **152**, or that first branch element **126** and third branch element **138** are equally affected by region **152**, and that neither first voltage signal V_1 nor third voltage signal V_3 needs to be modified.

Similarly, computing device **110** can also determine whether second branch element **132** and/or fourth branch element **144** is affected by region **152** by subtracting fourth voltage signal V_4 from second voltage signal V_2 to calculate a signal difference V_{2-4} (i.e., $V_{2-4}=V_2-V_4$). If difference V_{2-4} is greater than zero (i.e., if $V_{2-4}>0$), then computing device **110** determines that only second branch element **132** is affected by region **152**, and computing device **110** calculates a modified second voltage signal V_2' that accounts for (or cancels out) the effect of region **152** by subtracting difference V_{2-4} from second voltage signal V_2 (i.e., $V_2'=V_2-V_{2-4}$). If, on the other hand, difference V_{2-4} is less than zero (i.e., if $V_{2-4}<0$), then computing device **110** determines that only fourth branch element **144** is affected by region **152**, and computing device **110** calculates a modified fourth voltage signal V_4' that accounts for (or cancels out) the effect of region **152** by subtracting the absolute value of difference V_{2-4} from fourth voltage signal V_4 (i.e., $V_4'=V_4-|V_{2-4}|$). If, however, difference V_{2-4} equals zero (i.e., $V_{2-4}=0$), then computing device **110** determines that fourth voltage signal V_4 is equal to second voltage signal V_2 (i.e., $V_4=V_2$). Computing device **110** thus determines either that neither second branch element **132** nor fourth branch element **144** is affected by region **152**, or that second branch element **132** and fourth branch element **144** are equally affected by region **152**, and that neither second voltage signal V_2 nor fourth voltage signal V_4 needs to be modified.

After having determined which, if any, branch element(s) **126**, **132**, **138**, and/or **144** are affected by region **152**, and modifying the associated voltage signals(s) V_1 , V_2 , V_3 , and/or V_4 accordingly, computing device **110** can then calculate an output voltage signal V_τ that more accurately reflects the torque on component **102**. More specifically, to calculate output voltage signal V_τ , computing device **110** subtracts the sum of V_2 (or V_2') and V_4 (or V_4') from the sum of V_1 (or V_1') and V_3 (or V_3') (i.e., $V_\tau=(V_1 \text{ or } V_1')+(V_3 \text{ or } V_3')-[(V_2 \text{ or } V_2')+(V_4 \text{ or } V_4)']$). Output voltage signal V_τ is thus indicative of the true amount of torque on component **102**, as if region **152** was not present in component **102**. Notably, computing device **110** can perform such calcula-

tions in real time (e.g., as component **102** rotates), enabling continuous (or periodic) monitoring of the torque on component **102**.

As used herein, the term “voltage signal” refers to any type of signal that is indicative of an amount of voltage. As such, in relation to a voltage signal, the terms “increase,” “decrease,” “subtract from,” “account for,” “cancel out,” or any variation thereof refer to modifying the voltage signal in a manner that changes the amount of voltage of which the signal is indicative. Moreover, as used herein, a voltage signal is “modified” by either: altering a property of the signal itself so as to change the amount of voltage of which the signal is indicative; or by receiving the voltage signal which is indicative of a first amount of voltage and transmitting a new voltage signal indicative of a second amount of voltage that is different than the first amount of voltage.

As an example of system **107** in operation using sensor **117**, FIGS. **3** and **4** are schematic illustrations of sensor **117** when measuring torque on component **102** at a first residually magnetized region **158** of component **102** having a first angular position **160** and a second angular position **162**, respectively. More specifically, as component **102** rotates about axis **108**, first residually magnetized region **158** likewise rotates about axis **108**, thereby traveling from first angular position **160** to second angular position **162**. In that regard, FIG. **3** illustrates first residually magnetized region **158** at first angular position **160**, and FIG. **4** illustrates first residually magnetized region **158** at second angular position **162**.

When first residually magnetized region **158** has first angular position **160** (as shown in FIG. **3**), and thus affects only first branch element **126** and second branch element **132**, then: $V_1=(V_o+\sigma+\Delta)$; $V_2=(V_o-\sigma+\Delta)$; $V_3=(V_o+\sigma)$; and $V_4=(V_o-\sigma)$. Computing device **110** calculates output voltage signal V_τ as follows:

$$V_{1-3}=V_1-V_3=(V_o+\sigma+\Delta)-(V_o+\sigma)=+\Delta; V_{1-3}>0, \\ V_1'=V_1-V_{1-3}=(V_o+\sigma)$$

$$V_{2-4}=V_2-V_4=(V_o-\sigma+\Delta)-(V_o-\sigma)=+\Delta; V_{2-4}>0, V_2'=V_2- \\ V_{2-4}=(V_o-\sigma)$$

$$V_\tau=(V_1'+V_3)-(V_2'+V_4)=(V_o+\sigma)+(V_o+\sigma)-[(V_o-\sigma)+(V_o-\sigma)]=4\sigma$$

When first residually magnetized region **158** has second angular position **162** (as shown in FIG. **4**), and thus affects only third branch element **138** and fourth branch element **144**, then: $V_1=(V_o+\sigma)$; $V_2=(V_o-\sigma)$; $V_3=(V_o+\sigma+\Delta)$; and $V_4=(V_o-\sigma+\Delta)$. Computing device **110** calculates output voltage signal V_τ as follows:

$$V_{1-3}=V_1-V_3=(V_o+\sigma)-(V_o+\sigma+\Delta)=-\Delta; V_{1-3}<0, V_3'=V_3- \\ |V_{1-3}|=(V_o+\sigma)$$

$$V_{2-4}=V_2-V_4=(V_o-\sigma)-(V_o-\sigma+\Delta)=-\Delta; V_{2-4}<0, \\ V_4'=V_4-|V_{2-4}|=(V_o-\sigma)$$

$$V_\tau=(V_1'+V_3)-(V_2'+V_4)=(V_o+\sigma)+(V_o+\sigma)-[(V_o-\sigma)+(V_o-\sigma)]=4\sigma$$

As another example of system **107** in operation using sensor **117**, FIGS. **5** and **6** are schematic illustrations of sensor **117** when measuring torque on component **102** at a second residually magnetized region **164** of component **102** having a first angular position **166** and a second angular position **168**, respectively. More specifically, as component **102** rotates about axis **108**, second residually magnetized region **164** likewise rotates about axis **108**, thereby traveling from first angular position **166** to second angular position **168**. In that regard, FIG. **5** illustrates second residually

magnetized region **164** at first angular position **166**, and FIG. **6** illustrates second residually magnetized region **164** at second angular position **168**.

When second residually magnetized region **164** has first angular position **166** (as shown in FIG. **5**), and thus affects only first branch element **126**, then: $V_1=(V_o+\sigma+\Delta)$; $V_2=(V_o-\sigma)$; $V_3=(V_o+\sigma)$; and $V_4=(V_o-\sigma)$. Computing device **110** calculates output voltage signal V_τ as follows:

$$V_{1-3}=V_1-V_3=(V_o+\sigma+\Delta)-(V_o+\sigma)=+\Delta; V_{1-3}>0, \\ V_1'=V_1-V_{1-3}=(V_o+\sigma)$$

$$V_{2-4}=V_2-V_4=(V_o-\sigma)-(V_o-\sigma)=0; V_{2-4}=0, V_2'=V_2$$

$$V_\tau=(V_1'+V_3)-(V_2'+V_4)=(V_o+\sigma)+(V_o+\sigma)-[(V_o-\sigma)+(V_o-\sigma)]=4\sigma$$

When second residually magnetized region **164** has second angular position **168** (as shown in FIG. **6**), and thus affects only first branch element **126** and fourth branch element **144**, then: $V_1=(V_o+\sigma+\Delta)$; $V_2=(V_o-\sigma)$; $V_3=(V_o+\sigma)$; and $V_4=(V_o-\sigma+\Delta)$. Computing device **110** calculates output voltage signal V_τ as follows:

$$V_{1-3}=V_1-V_3=(V_o+\sigma+\Delta)-(V_o+\sigma)=+\Delta; V_{1-3}>0, \\ V_1'=V_1-V_{1-3}=(V_o+\sigma)$$

$$V_{2-4}=V_2-V_4=(V_o-\sigma)-(V_o-\sigma+\Delta)=-\Delta; V_{2-4}<0, \\ V_4'=V_4-|V_{2-4}|=(V_o-\sigma)$$

$$V_\tau=(V_1'+V_3)-(V_2'+V_4)=(V_o+\sigma)+(V_o+\sigma)-[(V_o-\sigma)+(V_o-\sigma)]=4\sigma$$

As yet another example of system **107** in operation using sensor **117**, FIG. **7** is a schematic illustration of torque sensor **117** when measuring torque on component **102** at a third residually magnetized region **170** of component **102**. Notably, third residually magnetized region **170** is sized and positioned such that, as component **102** rotates about axis **108**, third residually magnetized region **170** simultaneously affects all branch elements **126**, **132**, **138**, and **144** throughout each rotation of component **102**. More specifically, throughout each rotation of component **102**: $V_1=(V_o+\sigma+\Delta)$; $V_2=(V_o-\sigma+\Delta)$; $V_3=(V_o+\sigma+\Delta)$; and $V_4=(V_o-\sigma+\Delta)$. Thus, throughout each rotation of component **102**, computing device **110** calculates output voltage signal V_τ as follows:

$$V_{1-3}=V_1-V_3=(V_o+\sigma+\Delta)-(V_o+\sigma+\Delta)=0; V_{1-3}=0, V_1'=V_3$$

$$V_{2-4}=V_2-V_4=(V_o-\sigma+\Delta)-(V_o-\sigma+\Delta)=0; V_{2-4}=0, V_2'=V_4$$

$$V_\tau=(V_1'+V_3)-(V_2'+V_4)=(V_o+\sigma+\Delta)+(V_o+\sigma+\Delta)-[(V_o-\sigma+\Delta)+(V_o-\sigma+\Delta)]=4\sigma$$

The above-described embodiments include at least the following technical effects: (1) determining that a sensor is affected by a residually magnetized region of a component having a characteristic that the sensor is sensing; (2) accurately measuring a structural or functional aspect of the component (e.g., the torque on the component) by canceling out the effect of the component's residually magnetized region on the sensor; and (3) monitoring the structural or functional aspect of the component (e.g., the torque on the component) to identify when the aspect of the component exceeds a predefined value or is otherwise outside of a predefined range of values. Notably, the methods described herein can be realized in either the analog or digital domain.

The methods and systems described herein facilitate measuring the torque on a component using a torque sensor. More specifically, the methods and systems facilitate sensing an electromagnetic characteristic of the component using the torque sensor, and determining at a computer communicatively coupled to the sensor that the sensor is affected by

a residually magnetized region of the component. Moreover, the methods and systems facilitate generating a torque signal that negates the effect of the residually magnetized region of the component on the torque sensor. As such, the methods and systems facilitate a more accurate measurement of the torque on the component (e.g., a dynamic torque measurement), and thus facilitate a more accurate monitoring of the torque on the component (e.g., in real time). The methods and systems therefore facilitate extending the useful life of a rotating machine having the component by enabling a more accurate identification of when the torque on the component exceeds a predefined value or is otherwise outside of a predefined range of values.

Exemplary embodiments of systems and methods are described above in detail. The systems and methods described herein are not limited to the specific embodiments described herein, but rather, components of the systems and methods may be utilized independently and separately from other components described herein. For example, the systems and methods described herein may have other applications not limited to practice in measuring the torque on a rotatable component, as described herein. Rather, the systems and methods described herein can be implemented and utilized in connection with various other applications aside from torque-measurement.

While the invention has been described in terms of various specific embodiments, those skilled in the art will recognize that the invention can be practiced with modification within the spirit and scope of the claims.

The invention claimed is:

1. A system for measuring a structural or functional characteristic of a component having a residually magnetized region, said system comprising:

a torque sensor for sensing an electromagnetic characteristic of the component and transmitting a plurality of signals that are indicative of the electromagnetic characteristic; and

a computer communicatively coupled to said torque sensor for receiving the signals, said computer comprising a processor and a memory, said processor programmed to determine, using the signals, that said torque sensor is affected by the residually magnetized region of the component,

wherein said processor is programmed to compare the signals by comparing a first signal of a first pair of the signals with a second signal of the first pair of signals, and by comparing a third signal of a second pair of signals with a fourth signal of the second pair of signals.

2. A system in accordance with claim 1, wherein said torque sensor is a four-branch magnetostrictive torque sensor.

3. A system in accordance with claim 1, wherein the electromagnetic characteristic is a magnetic permeability of the component.

4. A system in accordance with claim 1, wherein said processor is programmed to compare the signals and make the determination by identifying that at least one of the signals is different than at least another one of the signals.

5. A system in accordance with claim 1, wherein said processor is programmed to modify at least one of the signals to account for the effect of the residually magnetized region.

6. A method for measuring a structural or functional characteristic of a component having a residually magnetized region, said method comprising:

transmitting, from a torque sensor that senses an electromagnetic characteristic of the component, a plurality of signals that are indicative of the electromagnetic characteristic;

receiving the signals at a computer that is communicatively coupled to the torque sensor and has a processor and a memory; and

determining, at the computer and using the signals, that the torque sensor is affected by the residually magnetized region of the component,

wherein said processor is programmed to compare the signals by comparing a first signal of a first pair of the signals with a second signal of the first pair of signals, and by comparing a third signal of a second pair of signals with a fourth signal of the second pair of signals.

7. A method in accordance with claim 6, wherein the torque sensor is a four-branch magnetostrictive torque sensor.

8. A method in accordance with claim 6, wherein the electromagnetic characteristic is a magnetic permeability of the component.

9. A method in accordance with claim 6, wherein said determining comprises, at the computer, comparing the signals and identifying that at least one of the signals is different than at least another one of the signals.

10. A method in accordance with claim 6, further comprising modifying, at the computer, at least one of the signals to account for the effect of the residually magnetized region.

11. A computer for measuring a structural or functional characteristic of a component having a residually magnetized region using a torque sensor that senses an electromagnetic characteristic of the component and transmits a plurality of signals that are indicative of the electromagnetic characteristic, said computer comprising:

a memory; and

a processor selectively coupled to the torque sensor for receiving the signals, said processor programmed to determine, using the signals, that the torque sensor is affected by the residually magnetized region of the component,

wherein said processor is programmed to compare the signals by comparing a first signal of a first pair of the signals with a second signal of the first pair of signals, and by comparing a third signal of a second pair of signals with a fourth signal of the second pair of signals.

12. A computer in accordance with claim 11, wherein the signals are indicative of a magnetic permeability of the component.

13. A computer in accordance with claim 11, wherein said processor is programmed to compare the signals and make the determination by identifying that at least one of the signals is different than at least another one of the signals.

14. A computer in accordance with claim 13, wherein said processor is programmed to determine that the at least one of the signals is different than the at least another one of the signals by subtracting the at least one of the signals from the at least another one of the signals to identify a difference therebetween.

15. A computer in accordance with claim 11, wherein said processor is programmed to modify at least one of the signals to account for the effect of the residually magnetized region.

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16. A computer in accordance with claim 11, wherein said processor is programmed to modify at least one of the signals to account for the effect of the residually magnetized region.

17. A computer in accordance with claim 13, wherein the signals are voltage signals.

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